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A New Design of Fuzzy Logic Control for SMES and Battery Hybrid Storage System

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Abstract

In this paper, the superconducting magnetic energy storage (SMES) and battery hybrid energy storage system has been designed to deal with high fluctuating power demand due to their complementary advantage. A lot of researchers are focusing on using battery technology to deal with low frequency demand and using SMES to deal with the remaining power demand. In this paper, a new energy management control method using 3 input parameters to a fuzzy logic controller is firstly proposed to deal with high fluctuating power demands. An example data processing result is shown in this paper. The results show that the hybrid storage system which applied fuzzy logic control has more flat battery charging/discharging current than an equivalent filtration control method. The low fluctuating battery demand is ideal for extending battery lifetime. Furthermore, the fuzzy logic controller can automatically adapt to the size of the SMES system by applying the state of the charge (SOC) of SMES as an input parameter to the fuzzy logic control.

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Keywords: superconductor magnetic energy storage (SMES) and battery hybrid storage system; fuzzy logic control; energy management; battery lifetime extention; power demand;

1. Introduction:

In the recent years, SMES and battery hybrid energy storage systems have been proposed as alternatives for many conventional energy storage systems. Batteries are the most commonly used energy storage device which have high energy capacity and low prices. On the other hand, SMESs have high power density which means it can charge or discharge at very high power [1] [2]. Long service lifetime and almost infinite charge/discharge cycle make SMES a perfect solution to deal with high fluctuating power demand [3] [4] [5]. However, the low energy density of SMESs limits the applications for using it to deal with fluctuating power for an extended period of time. SMES and battery hybrid storage systems combine the advantages

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of high power density, fast responding speed and infinite switching times with the high energy density characterised by batteries [6].

By using a hybrid configuration, the sizing of SMESs can be reduced and the battery service lifetime can be extended. Battery lifetime can be affected by the charging/discharging rate. Rapid change of battery current will shorten the battery lifetime [7] [8]. The ideal usage of battery technology would be while constant current is being drawn.

Many researchers have fed power demand into a low-frequency pass filter and only the low frequency demand is compensated by the battery as shown in Fig.1 [9] [10]. The remaining power demand is dealt by the SMES. Due to the feature of a low pass filter, the battery current would be unstable under high fluctuation situations.

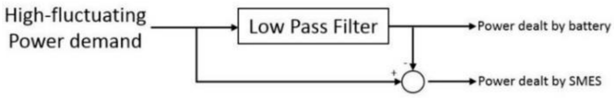

Fig.1. The scheme of filtration control method power share

In this study, a novel fuzzy logic control strategy for SMES and battery hybrid storage system energy management is firstly proposed. Using the new control strategy allows the battery current to be more constant than the low-frequency filter method in the same fluctuating power demand cases. The proposed fuzzy logic control strategy also considers the state-of-charge for the SMES system, which makes this control strategy adaptive for any size of SMES magnet.

2. Configuration of the hybrid storage system and control method

2.1 Configuration of hybrid storage system

Fig.2 shows the configuration of the hybrid storage system. The battery and SMES are parallel connected. The combination of the Voltage Source Converter (VSC), bi-directional DC/DC converter and the chopper allow energy to be drawn and supplied to the power source, in this case the power grid.

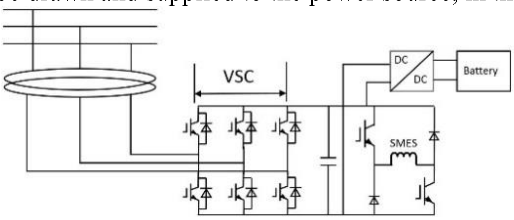

Fig.2. Configuration of the battery and SMES hybrid storage system

2.2 Power management scheme of hybrid storage system:

The fuzzy logic control rule is based on 'trial and error' [11] [12] method to control the battery power output, the rest of the power demand is dealt by SMES.

$$P_{SMES}=P_{demand}-P_{battery} \quad (1)$$

The choice of fuzzy logic controller input parameters is very important. The fuzzy logic controller is designed to control the battery charge/discharge gradient. By setting this parameter as the output the battery charge/discharge current can be made relatively flat, which can extend battery lifetime. Battery power can be calculated by the follow equations:

$$P_{change(k)}=P_{change(k-1)}+P_{fuzzy\_out(k)} \tag{2}$$

$$P_{battery(k)}=P_{battery(k-1)}+P_{change(k)} \tag{3}$$

In this study, not only the power difference between demand and battery output is considered but also the SOC of SMES magnet. This consideration can make sure the control method adapt to any size of SMES magnet. The third input provides information concerning the previous battery power output levels according to Equation. 4.

$$\textit{Input 3}= (P_{demand(k)}-P_{battery(k-1)})-P_{battery(k-1)}-P_{battery(k-2)}) \tag{4}$$

The control configuration is shown in Fig.3, P_{demand} means demand power P_B means battery output power, ΔP_B means change of battery output power. k means the value at kth sampling instant.

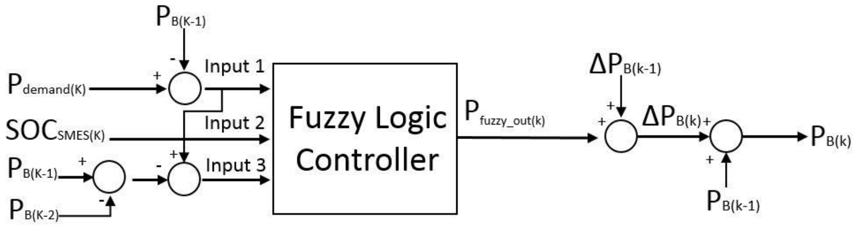

Fig.3. The control configuration of fuzzy logic control

3. Fuzzy logic controller for energy management system

3.1 Brief review of fuzzy logic

The fuzzy logic controller is composed of three parts: Fuzzification part, decision making part and defuzzification part [13]. Fuzzification is to classify input data into suitable linguistic values. The larger the number of fuzzy levels the higher is the input resolution. Decision making part include rules and database which can generate inferred fuzzy value. The designer can apply their knowledge and experience to decide rules and database, which makes the fuzzy logic controller more intelligent. The defuzzification part can convert the inferred fuzzy value to real crisp value. The crisp value is used to control the system.

3.2 Fuzzy logic controller design

In this energy management fuzzy logic controller, three parameters are selected for fuzzy logic input as discussed in section 2.2. The membership function for the input 1 is shown in Fig.3, input 3 is similar with input 1. Input 2 only has three level which is used to simplify the control rule.

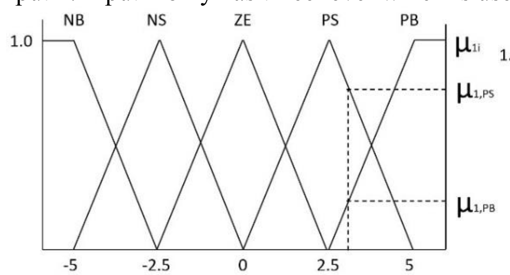

Fig.3. Membership function of input 1

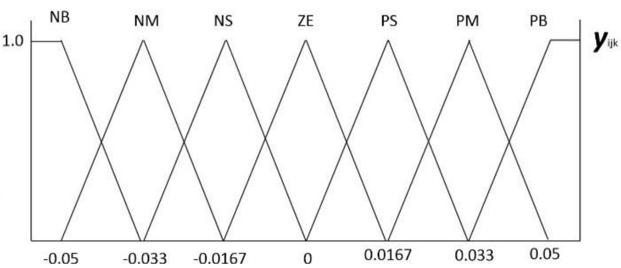

Fig.4. Output value of consequent

The output membership function has seven parts, which can help the controller to make more accurate output control. The control rule is based on ‘trial and error’ method to control the output. The control rules are shown in table 1. There are some abbreviations in table.1 to make the control rule more understandable: NB (negative big), NM(negative medium),NS(negative small),ZE(zero),PS(positive small),PM(positive medium),PB(positive big).

Table.1. control rules of hybrid storage system

Input 1	NB	NB	NB	NB	NB	NB	NB	NB	NB	NB	NB	NB	NB	NB	NB
Input 2	NB	NB	NB	NB	NB	ZE	ZE	ZE	ZE	ZE	PB	PB	PB	PB	PB
Input 3	NB	NS	ZE	PS	PB	NB	NS	ZE	PS	PB	NB	NS	ZE	PS	PB
Output	NB	NM	NS	ZE	PS	NM	NS	ZE	PS	PM	NB	NM	NS	ZE	PS
Input 1	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Input 2	NB	NB	NB	NB	NB	ZE	ZE	ZE	ZE	ZE	PB	PB	PB	PB	PB
Input 3	NB	NS	ZE	PS	PB	NB	NS	ZE	PS	PB	NB	NS	ZE	PS	PB
Output	NM	NS	ZE	PS	PM	NS	ZE	ZE	ZE	PS	NM	NS	ZE	ZE	PS
Input 1	ZE	ZE	ZE	ZE	ZE	ZE	ZE	ZE	ZE	ZE	ZE	ZE	ZE	ZE	ZE
Input 2	NB	NB	NB	NB	NB	ZE	ZE	ZE	ZE	ZE	PB	PB	PB	PB	PB
Input 3	NB	NS	ZE	PS	PB	NB	NS	ZE	PS	PB	NB	NS	ZE	PS	PB
Output	NS	ZE	ZE	PS	PM	NS	ZE	ZE	ZE	PS	NM	NS	ZE	ZE	PS
Input 1	PS	PS	PS	PS	PS	PS	PS	PS	PS	PS	PS	PS	PS	PS	PS
Input 2	NB	NB	NB	NB	NB	ZE	ZE	ZE	ZE	ZE	PB	PB	PB	PB	PB
Input 3	NB	NS	ZE	PS	PB	NB	NS	ZE	PS	PB	NB	NS	ZE	PS	PB
Output	NS	ZE	ZE	PS	PM	NS	ZE	ZE	ZE	PS	NM	NS	ZE	PS	PM
Input 1	PB	PB	PB	PB	PB	PB	PB	PB	PB	PB	PB	PB	PB	PB	PB
Input 2	NB	NB	NB	NB	NB	ZE	ZE	ZE	ZE	ZE	PB	PB	PB	PB	PB
Input 3	NB	NS	ZE	PS	PB	NB	NS	ZE	PS	PB	NB	NS	ZE	PS	PB
Output	NS	ZE	PS	PM	PB	NM	NS	ZE	PS	PM	NS	ZE	PS	PM	PB

The defuzzificated value is given by:

$$y_o = \frac{\sum i \sum j \sum k min\{\mu_{1i}(x_1)\cdot\mu_{2j}(x_2)\cdot\mu_{3k}(x_3)\}\cdot y_{ijk}}{\sum i \sum j \sum k min\{\mu_{1i}(x_1)\cdot\mu_{2j}(x_2)\cdot\mu_{3k}(x_3)\}} \tag{5}$$

Where i, j and k express NB, NS, NS, ZE, PS, PM, PB and y_{ijk} determined by the control rules and membership functions of the consequent value. The output value y_0 is the $P_{fuzzy\_out(k)}$ in Eq. 5.

4. Results and discussion

The proposed fuzzy logic control method is applied to the energy management system. In this paper, one example data set is shown in Fig. 5. The dataset is fed to both the filtration control method and the novel proposed control method. The SMES size in the hybrid systems are the same when applying the two control methods. The results are shown in Fig.6 and Fig.7:

As can be seen from Fig.6 and Fig.7, in the first 200 seconds of the fuzzy logic control method, the battery starts to charge the SMES to raise the SMES SOC to a suitable value. This makes the battery output power relatively higher than the filtration control method. The result shows that battery power output of the new proposed control method is much more flat than the filtration control method, which is good for extending the battery lifetime.

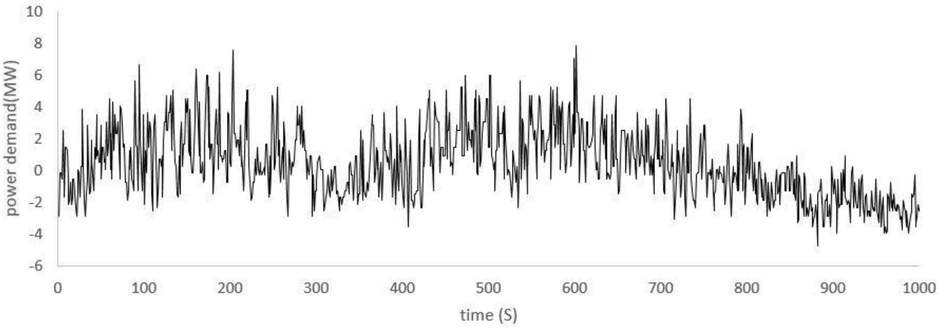

Fig.5 Example power demand

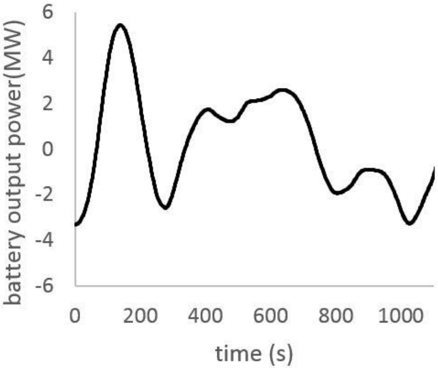

Fig.6 Battery power output by using fuzzy logic control

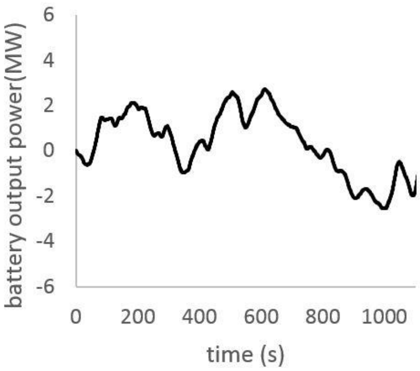

Fig.7 Battery output by using filtration control

There is not much battery output power fluctuation for the proposed control method. At time 500s to 550s and 850s to 950s, the new control method significantly stabilises the power output compared with the filtration control method. During 660s to 780s, the new control method makes the battery power output more smoothly than the filtration control.

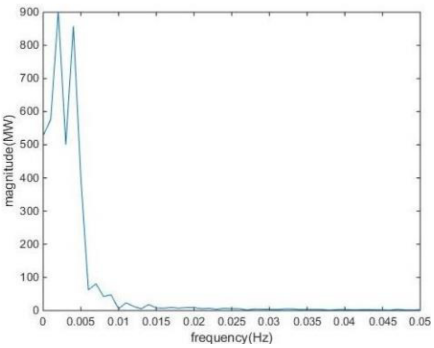

Fig. 8 Fourier analysis of battery output (fuzzy logic method)

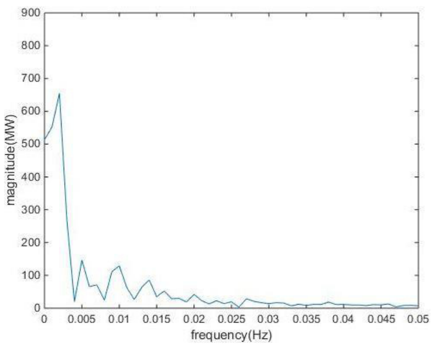

Fig. 9 Fourier analysis of battery output (filtration method)

As for battery, the ideal performance of the battery should be working at low frequency fluctuation. Fourier analysis of the battery performance for both proposed method and filtration method are shown in figure.8 and figure.9. From the results, the proposed method has high magnitude at very low frequency which means the proposed method has more stable power output compared with the filtration method. The total battery power output is the same, the proposed control method has higher magnitude of low fluctuating power and lower magnitude of high fluctuating power compared to the filtration method. Less high frequency fluctuating power can extend battery lifetime.

The other advantage of the proposed method is that the proposed control method considers the SMES SOC level. For the different size of SMES in the hybrid system, the control system can still work properly. When the SMES SOC is at a suitable value and power fluctuation is in a suitable range, the battery power does not change a lot. The designer can define the expected suitable value in the fuzzy logic controller. The values are based on the designer's knowledge and experience. During the SMES SOC level at a suitable value, the SMES is capable of dealing with the power demand itself, the battery output nearly does not change.

5. Conclusion:

A computing simulation performance have been done for applying the proposed novel fuzzy logic control method. The novel 3 input fuzzy logic controller considers both the SMES SOC level and power demand. The controller controls the battery power output gradient. Meanwhile, the controller can adapt to any size of SMES due to one input parameter being the SOC level. The results show that the proposed control method can make the battery output more stable compared with the filtration control method for the same size of hybrid storage system.

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